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MHTGR RADIONUCLIDE SOURCE TERMS FOR USE IN SITING

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Abstract - This paper presents the site suitability source terms for the Modular High Temperature Gas-Cooled Reactor (MHTGR). The MHTGR program has identified a spectrum of accident release scenarios that form a basis for determining the MHTGR site suitability source terms. This basis, consistent with 10CFR100 guidelines, includes an evaluation of a spectrum of accidents to determine a set of conservative source terms. The spectrum of accidents is represented by a set of Licensing Basis Events (LBEs). The subset of LBEs that involve radionuclide release from the plant is identified. The MHTGR approach evaluates site suitability with respect to the regulatory criteria applicable not only for off-normal events, but also for normal operation and emergency planning. The radionuclide inventories available for potential release from the MHTGR and the release behavior of these inventories are characterized. A summary of the source terms for selected key radionuclides are given. The time-dependent MHTGR source terms account for a mix of accident phenomena, failure states of barriers, number of reactor modules, and chemical attack conditions that are consistent with the unique characteristics of the MHTGR.

SELECTION OF RADIONUCLIDE RELEASE SCENARIOS

The criteria to evaluate suitability of proposed sites for stationary nuclear power reactors under various radionuclide release scenarios are described in 10CFR100.[1] To facilitate the evaluation process, 10CFR100[1] provides generic guidance to develop source terms by considering a spectrum of postulated radionuclide release scenarios that would result in potential hazards not exceeded by those from any accident considered credible." Thus, the identification of credible, postulated radionuclide release scenarios for the MHTGR[2] is the first step in the evaluation of siting suitability.

A spectrum of possible radionuclide release scenarios was identified for the MHTGR program, consisting of a set of LBEs, to form a basis for determining the site suitability source terms. The selected LBEs are consistent with 10CFR100 guidelines and yield a set of conservative source terms. These MHTGR LBEs, shown in Table 1, are further characterized by the following:

1. They are logically chosen, following a structured method to consider a wide spectrum of possible events. Events were selected by a safety risk assessment [Level 3 per Nuclear Regulatory Commission (NRC) NUREG/CR 2300[5]].

2. They are bounding, by considering all conceivably credible accidents including those not expected to occur in the lifetime of several hundred MHTGR plants (down to a mean frequency of 5×10^{-7}/plant year).

3. They are comprehensive, since they account for a mix of accident scenarios yielding varying release rates, release mixes, failure states of barriers, and release from multiple reactor modules.

4. The radionuclide release estimates are conservative, since they include uncertainties combined satistically in calculations.

5. The radionuclide release estimates include enhanced safety margins, consistent with NRC's Advanced Reactor Policy.[6]

Table 1 shows specific release scenarios that contribute to radionuclide release from the plant, since not all scenarios result in release of radionuclides from the plant. The mean frequency and the applicable criteria against which compliance is demonstrated are identified in Table 1. The MHTGR approach for site suitability evaluation includes compliance with the regulatory criteria that are applicable not only for off-normal events, but also for normal operation and emergency planning.

Approach to radionuclide control

The MHTGR configuration was developed to ensure the integrity of the standard (no defect and within specification) fuel particles such that the radionuclide inventory is retained within the fuel particles under all credibly conceivable events. Thus, the only available significant source for potential radionuclide release is outside the standard particles.

Table 2 illustrates, for example, sources of I-131 (which is the dominant contributor to thyroid dose) available for release in one module and the relative timing characteristics of associated release mechanisms. As shown, the smallest sources, the circulating and plateout activities within the primary circuit, have the potential for the fastest release to the reactor building. Because this release is linked to the accidental leakage of the gaseous helium coolant from the vessel system, this release could characteristically occur within minutes.

The remaining sources of I-131 radionuclide are within the core graphite, but outside of standard, intact particles, and take longer to be released. Since the mechanisms for release from these defective fuel particles depend on core temperature, which increases very slowly due to the large heat capacity of the massive graphite moderator and low power density of the core, these releases characteristically occur over hours to many days. However, it is possible for a small fraction of the inventory from fuel particles with as-manufactured defective coatings to be released rapidly. The potential for such a rapid release (minutes to hours) from these defective particles is postulated with events in which high core temperatures occur coincident with a large moisture ingress providing reactants that can hydrolyze the carbide portion (approximately 7%) of the UCO fuel.

In summary, the potential activity releases, as shown in Table 2, can be grouped into two broad categories, a small early release and a larger delayed release.

Normal operation releases

Insignificantly small quantities of radionuclide effluents to the environment in the form of gases and liquids occur during the normal MHTGR plant operation. These releases result from the radioactive gas waste system and liquid waste system, respectively. Table 3 provides a summary of expected annual gaseous and liquid release from a four module MHTGR plant. The concomitant doses for gaseous effluent releases are well below 10CFR50 Appendix I limits,[3] with margins of an order of magnitude or higher. In comparison, the expected radioactive liquid effluent releases have margins of five to eight orders of magnitude against the maximum concentration limits of 10CFR20.[7]

Off-normal event releases

A mechanistic assessment of the off-normal events was performed and a summary of the equilibrium source terms for a few key radionuclides are given in Table 4 for release scenarios that could result in potential radionuclide release from the plant. The source terms shown in Table 4 are for a single, specific, and independent event and therefore the source terms are not additive. Further, the MHTGR plant is located primarily below grade with no stack and hence any potential radionuclide releases are contained at or below ground level.

The equilibrium source terms shown in Table 4 are insignificantly small. Thus, the resulting offsite does are negligibly small and are well within the Protective Action Guides[4] and hence do not require drills for offsite public sheltering or evacuation.

Table 1. MHTGR release scenarios selected for site suitability source terms.

Release Scenarios	Frequency/Plant Year	Applicable Criteria
Small releases associated with RCCS air and other service system sources	Normal plant operation	10CFR50 Appendix I[3]
Small primary coolant leak with forced core cooling (AOO-5)	0.3	10CFR50 Appendix I[3]
Moisture inleakage without forced core cooling (DBE-7)	5×10^{-5}	10CFR100[1]
Primary coolant leak with forced core cooling (DBE-10)	0.01	10CFR100[1]
Primary coolant coolant leak without forced core cooling (DBE-11)	3×10^{-4}	10CFR100[1]
Moisture inleakage with delayed steam generator isolation and without forced core cooling (EPBE-1)	3×10^{-7}	Lower PAG (sheltering)[4]
Moisture inleakage with delayed steam generator isolation and with forced core cooling (EPBE-2)	4×10^{-6}	Lower PAG (sheltering)[4]
Primary coolant leak in <u>four</u> modules without forced core cooling (EPBE-3)	7×10^{-7}	Lower PAG (sheltering)[4]

Legend
- AOO = Anticipated operational occurrences
- ADE = Design basis events
- EPBE = Emergency planning basis events

TABLE 2
I-131[a] INVENTORY AVAILABLE FROM A SINGLE MODULE MHTGR FOR POTENTIAL RELEASE

Source Characterization	Inventory (Ci)	Timing of Release	Release Mechanisms: From Core	Release Mechanisms: From Primary Circuit
A. Circulating	0.02	Minutes	--	Leakage flow (He depressurization)
B. Plateout	20.0	Minutes	--	Leakage flow (He depressurization) and moisture (water ingress)
C. Outside standard particles				
1. Nonintact [failed SiC[b] and OPyC[b]]	465.0	Hours[c]-days	Temperature (loss of forced cooling) and moisture (water ingress)	Leakage flow (He depressurization)
2. Contamination	93.0	Hours-days	Temperature (loss of forced cooling)	Leakage flow (He depressurization)
D. Standard particles	9.3×10^6	> days	Temperature (no event identified)	--

[a]Contributes to thyroid dose.
[b]Silicon carbide (SiC); outer pyrolytic carbon (OPyC).
[c]Approximately 33 curies of the inventory (representing the UC_2 in nonintact fuel particles) is subject to release within minutes under hydrolyzing conditions that may be encountered in rare MHTGR accidents.

Table 3. Radionuclide effluents from a four module MHTGR during normal plant operation.

Nuclide	MHTGR Releases (Ci/Year)
A. Expected Annual Gaseous Release	
H-3	10
Kr-85	40
Xe-133	10
Ar-41	20
B. Expected Annual Liquid Release	
I-131	4.9×10^{-6}
Cs-137	2.2×10^{-4}
Ba-140	3.1×10^{-7}

TABLE 4
MHTGR EQUILIBRIUM SOURCE TERMS OF KEY NUCLIDES FOR LICENSING BASIS EVENTS

LBE	No. of Modules	Release Duration (h)	Cumulative Fractional Release to the Environment[a]			
			Kr-88	Sr-90	I-131	Cs-137
AOO-5	1	0 to 1.25	1.4×10^{-7}	1.1×10^{-11}	3.1×10^{-10}	1.5×10^{-10}
DBE-7	1	0 to 0.02	7.5×10^{-9}	5.4×10^{-9}	3.1×10^{-8}	9.2×10^{-7}
DBE-10	1	0 to 1	2.2×10^{-7}	1.[illegible] $\times 10^{-10}$	8.0×10^{-10}	3.4×10^{-9}
DBE-11	1	0 to 8 0 to 100	2.4×10^{-8} 3.3×10^{-8}	2.2×10^{-12} 9.9×10^{-12}	4.5×10^{-9} 2.8×10^{-7}	2.6×10^{-11} 4.4×10^{-11}
EPBE-1	1	0 to 8 0 to 100	9.7×10^{-7} 9.9×10^{-7}	4×10^{-8} 4×10^{-8}	3.6×10^{-7} 4.9×10^{-7}	3.6×10^{-6} 3.8×10^{-6}
EPBE-2	1	0 to 8	2.6×10^{-7}	1.1×10^{-7}	3.6×10^{-7}	1.9×10^{-5}
EPBE-3	4	0 to 8 0 to 100	8.2×10^{-8} 1.6×10^{-7}	8.2×10^{-12} 3.8×10^{-11}	1.5×10^{-8} 9.5×10^{-7}	1.0×10^{-10} 1.7×10^{-10}

[a]Fractions of initial radionuclide inventory (single module) of 9.9×10^6 Ci of Kr-88, 7.4×10^5 Ci of Sr-90, 9.3×10^6 Ci of I-131, and 8.6×10^5 Ci of Cs-137.

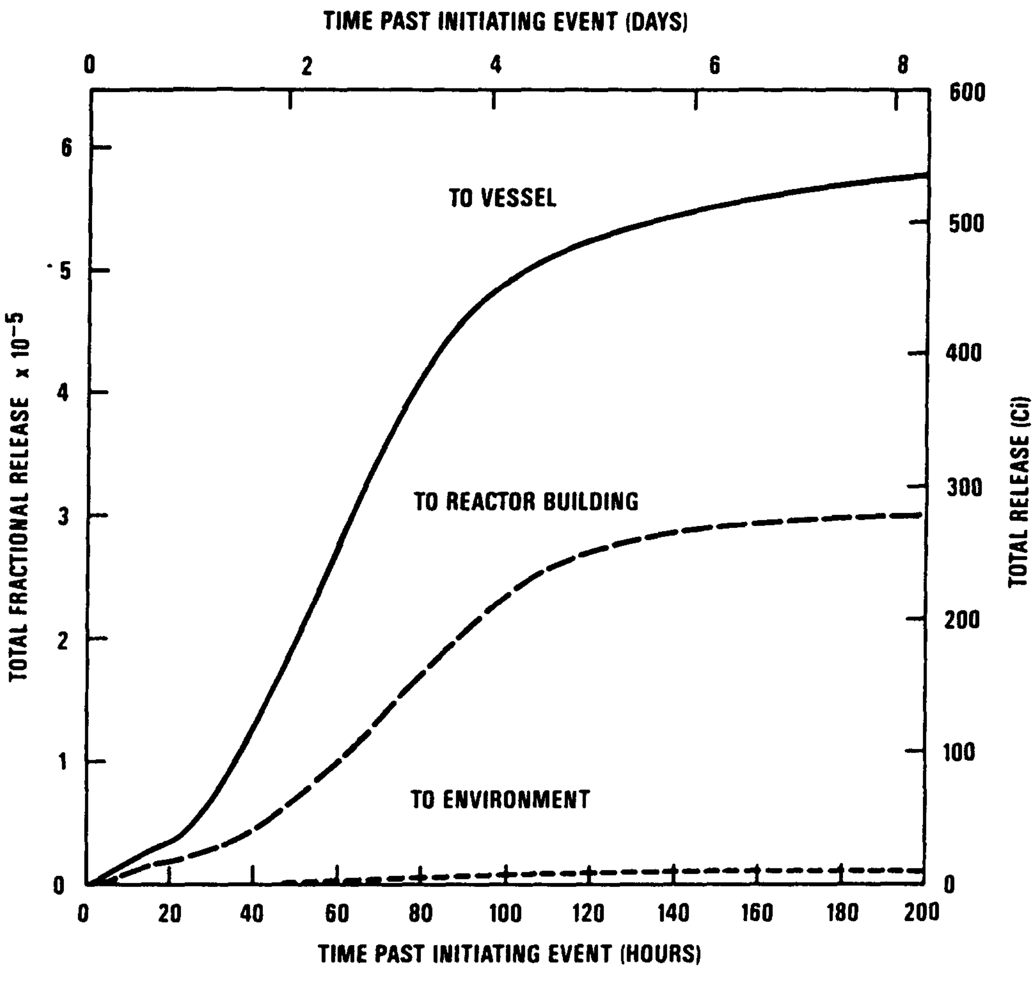

Fig. 1. MHTGR cumulative retention of I-131 during EPBE-3

The time dependence of the release of the radionuclide I-131 from the core due to a loss of core cooling and a loss of coolant in all four modules for one specific event (EPBE-3) is shown in Fig. 1 for illustration. As seen, the release occurs slowly spanning several days. The release from the reactor vessel to the reactor building is limited due to radioactive decay and the lack of a driving force from the reactor vessel. The slow release characteristics allow further retention in the reactor building by naturally occurring physical phenomena such as plateout and settling. Since there is no driving force to transport radionuclides out of the reactor building, the radionuclide release to the environment is further limited.

In summary, the cumulative source terms developed for the MHTGR plant siting suitability include a mix of release scenarios, failure states of barriers, and multiple reactor modules.

CONCLUSION

The inherent characteristics and passive safety features of the MHTGR provide a solid basis for developing a mechanistic basis for siting. The MHTGR site suitability source terms can be characterized and evaluated by a representative set of potential release scenarios and resultant radionuclide releases to the environment. An evaluation shows that the source terms developed for the siting suitability of the MHTGR are benign, requiring no sheltering or evacuation of the public beyond the site boundary.

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